Spectroscopy and continuous-wave diode-pumped laser action of $Yb^{3+}:YVO_4$

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The growth, spectroscopic properties, and laser performance of Yb:YVO_4 crystal with laser diode pumping are reported. A peak absorption cross section of 7.4×10^{-20} cm^2 at 985 nm, a radiative lifetime of 0.25 ms, and a stimulated-emission cross section of 1.25×10^{-20} cm^2 at 1008 nm for π polarization were determined for the Yb^{3+} ions in YVO_4. Continuous-wave laser action of Yb:YVO_4 at 1020–1027 nm was demonstrated with an output power of 610 mW and a slope efficiency of 49%.

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Crystals doped with trivalent ytterbium ions (Yb^{3+}) are of great interest for directly diode-pumped high power lasers in the spectral range near 1 μm.[1] The features of the Yb^{3+} ion are a simple two-level electronic structure that eliminates losses resulting from upconversion and excited-state absorption, a low quantum defect between the pump and the laser wavelengths that strongly reduces heat generation, and a broad emission (gain) bandwidth that enables one to tune the laser wavelength over 20–100 nm and to generate femtosecond pulses.[1,2] Yttrium vanadate (YVO_4) crystals doped with different rare-earth ions (Nd, Er, Tm, and Ho; Refs. 3 and 4) exhibit efficient laser action and are thus attractive hosts for Yb ions. YVO_4 is an optically uniaxial crystal and demonstrates moderate thermomechanical properties.[4] The thermal conductivity of YVO_4 crystal is 5.23 W/mK along the c axis and 5.10 W/mK along the a axis, values that are lower than in YAG. However, these values are approximately 40% higher than in the well-known $KGdWO_4$ host crystal for Yb ions.[2] Recent efforts in the optimization of growth techniques allow one to produce large Yb:YVO_4 single crystals of optical quality with a high Yb content (up to 18% in Ref. 5). Here we report, for the first time to our knowledge, spectroscopic properties and efficient room-temperature cw laser action of Yb:YVO_4 single crystals.

One of the problems in the fabrication of YVO_4 single crystals of high optical quality is the disturbance of stoichiometry during crystal growth because of the low melting point (680 °C) and high vapor pressure of V_2O_5. To reduce nonstoichiometry a solid phase of YVO_4 as raw material for crystal growth has to be synthesized at a temperature below 680 °C. The synthesis of the raw material was conducted at 600 °C by use of V_2O_5 and crystalline yttrium hydrate, which has a low melting point in the stoichiometric ratio. The crystals were grown by Solix, Ltd., by use of the Czochralski technique in an iridium crucible in an argon atmosphere containing oxygen. The pulling rate was approximately 2–3 mm/h with a rotation speed of 10–15 rpm. The Yb concentration in the melt was 2–3 at.%. Boules of Yb:YVO_4 single crystals of high optical quality that were 30 mm in diameter and 35 mm in length were produced. Optical losses in the emission range were estimated to be no higher than 0.001 cm^{-1}.

YVO_4 has a tetragonal lattice with the D_{4h} ($4/mmm$) space group.[4] The room-temperature polarized absorption spectra of a $Yb^{3+}:YVO_4$ crystal measured with 0.4-nm spectral resolution are shown in Fig. 1. A strong absorption band is observed at 985 nm for π polarization ($E \parallel c$) with a peak absorption coefficient of ~14.7 cm^{-1} and a 5-nm bandwidth (FWHM). The concentration of Yb ions in the crystal was determined from atomic emission analysis to be 2×10^{20} cm^{-3}, which corresponds to 1.62 at.%. The distribution coefficient (the ratio of Yb concentrations in the crystal and in the melt) was estimated to be 0.78. This crystal was also used for lifetime measurements and laser experiments.

It is well known that radiation trapping strongly affects the measured lifetime of Yb-doped materials because of significant overlap of the absorption and emission bands.[6] The comparatively high index of refraction of YVO_4 ($n_0 = 1.957$) also increases the probability of reabsorption even in optically thin samples

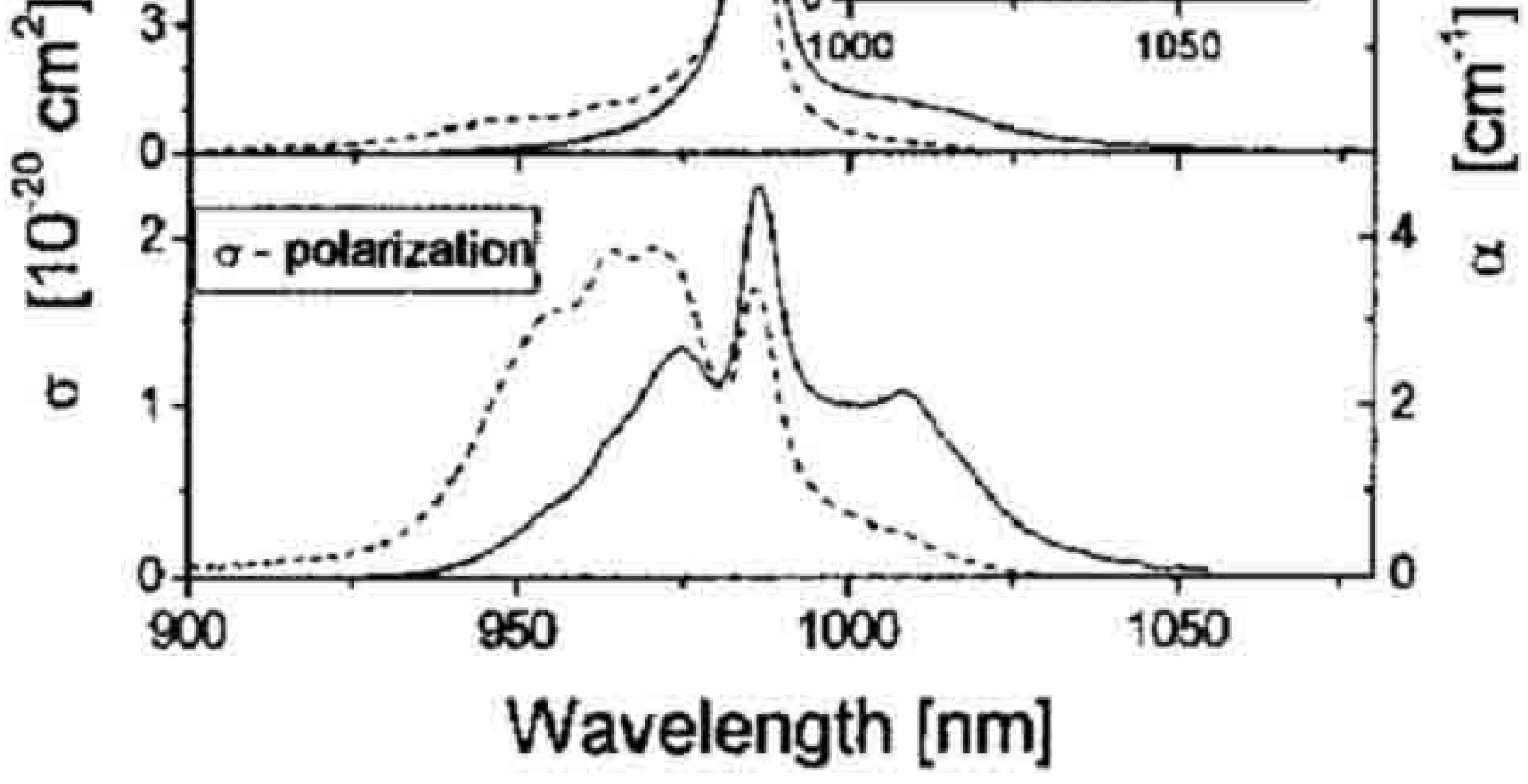

Fig. 1. Polarized absorption and emission spectra of $Yb^{3+}:YVO_4$ at room temperature.

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because of the total internal reflection. Thus the special methods discussed in the literature[6,7] should be used to determine the radiative lifetime accurately. In our experiments we used a fine powder of Yb(1.62%):YVO$_4$ crystal immersed in glycerin for lifetime measurements. The diameter of the powder particles was measured to be approximately 40–70 μm, several times lower than the Yb^{3+} absorption length (375 μm at 985 nm). As an excitation source a tunable Ti:sapphire laser with a pulse duration of ~7 ns was used. The luminescence of a sample passed through a 0.3-m monochromator and was registered by a fast Ge photodiode coupled with a 500-MHz digital oscilloscope. For the powder samples in glycerin the lifetime decreased with decreasing powder concentration in suspension. Starting from a certain powder content, the lifetime remained constant despite further dilution (Fig. 2), thus indicating that reabsorption effects became negligible. Taking into account that the luminescence quantum yield of this crystal at room temperature is close to 1, we believe that the measured value of (247 ± 5) μs corresponds to the radiative lifetime of Yb^{3+} in YVO$_4$.

Using the data on Yb content in the crystal, we estimated the peak absorption cross section of Yb^{3+} in YVO$_4$ to be 7.4×10^{-20} cm^2 at 985.4 nm for π polarization (Fig. 1). The stimulated-emission cross section was calculated by use of the modified reciprocity method,[8] in which it is not necessary to know the Stark level structure of the Yb^{3+} manifolds ($^2F_{5/2}$ and $^2F_{7/2}$):

$$\sigma_{\mathrm{em}}^{\alpha}(\lambda) = \frac{3\exp[-hc/(kT\lambda)]}{8\pi n^2 \tau_{\mathrm{rad}} c\{\sum_\beta \int \lambda^{-4}\sigma_{\mathrm{abs}}^{\beta}(\lambda)\exp[-hc/(kT\lambda)]\mathrm{d}\lambda\}}\,\sigma_{\mathrm{abs}}^{\alpha}(\lambda), \tag{1}$$

where τ_{rad} is the radiation lifetime of an active center; c is the velocity of light; α is the light polarization; h and k are Planck and Boltzmann constants, respectively; T is the host crystal temperature; n is the refractive index of a crystal; β denotes the polarization state; and σ_{abs} is the ground-state absorption cross section. The stimulated-emission cross section was estimated with this method to be 1.25×10^{-20} and 1.1×10^{-20} cm^2 at 1008 nm for π and σ polarization, respectively. In comparison with Yb-doped KGdWO$_4$, the crystal of Yb:YVO$_4$ exhibits a stimulated-emission cross section that is approximately twice as low, a close radiative lifetime, and broader absorption and emission bands.

The laser experiments were carried out with a nearly hemispherical laser cavity. It consisted of a 50-mm radius-of-curvature output coupler (OC) and a plane mirror highly reflecting at 1020–1100 nm. Yb:YVO$_4$ crystal was cut along the a axis for possible operation in both the π and σ polarizations ($E \parallel c$ and $E \perp c$). The laser element, with a thickness of 2.4 mm, was antireflection coated at the pump and laser wavelengths and mounted on an aluminum heat sink kept at 10 °C. A cw fiber-coupled (ø = 100 μm, N.A. of 0.22) laser diode with a maximum output power of ~8 W at 984 nm was used for longitudinal pumping of the active element through a plane mirror. This mirror has only 63% transmission at the pump wavelength, reducing a maximum incident pump power at the crystal down to 5 W. The pump beam was focused to a 110-μm spot with a confocal length of ~2.5 mm inside the laser crystal. The cavity-mode diameter for the TEM$_{00}$ transverse mode at the active element was close to the pump beam waist.

Input–output diagrams for the Yb:YVO$_4$ laser in the cw regime with OC transmittances of 1% and 4% are presented in Fig. 3. A maximum output power of ~610 mW at 1020 nm for a TEM$_{00}$ mode with a slope efficiency of 49% with respect to the absorbed pump power was obtained with 4% OC transmittance. For a Yb:YVO$_4$ laser with OC transmittance of 1% the slope efficiency was decreased to 39% with an output power of 555 mW at 1027 nm. In both cases the laser output was π polarized, where the stimulated-emission cross section was higher than for σ polarization and equal to 0.8×10^{-20} cm^2 at 1020 nm and 0.5×10^{-20} cm^2 at 1027 nm. Laser thresholds for the 1% and 4% OCs were estimated to be 550 and 850 mW of the absorbed pump power, respectively. The nonlinear input–output characteristics and shift of the laser wavelength with a change in the OC transmittance were typical for Yb lasers and were attributed to the nonsaturated reabsorption losses in the range of gain because of the three-level laser scheme of the Yb^{3+} ion. In comparison with Yb:KGdWO$_4$ and other

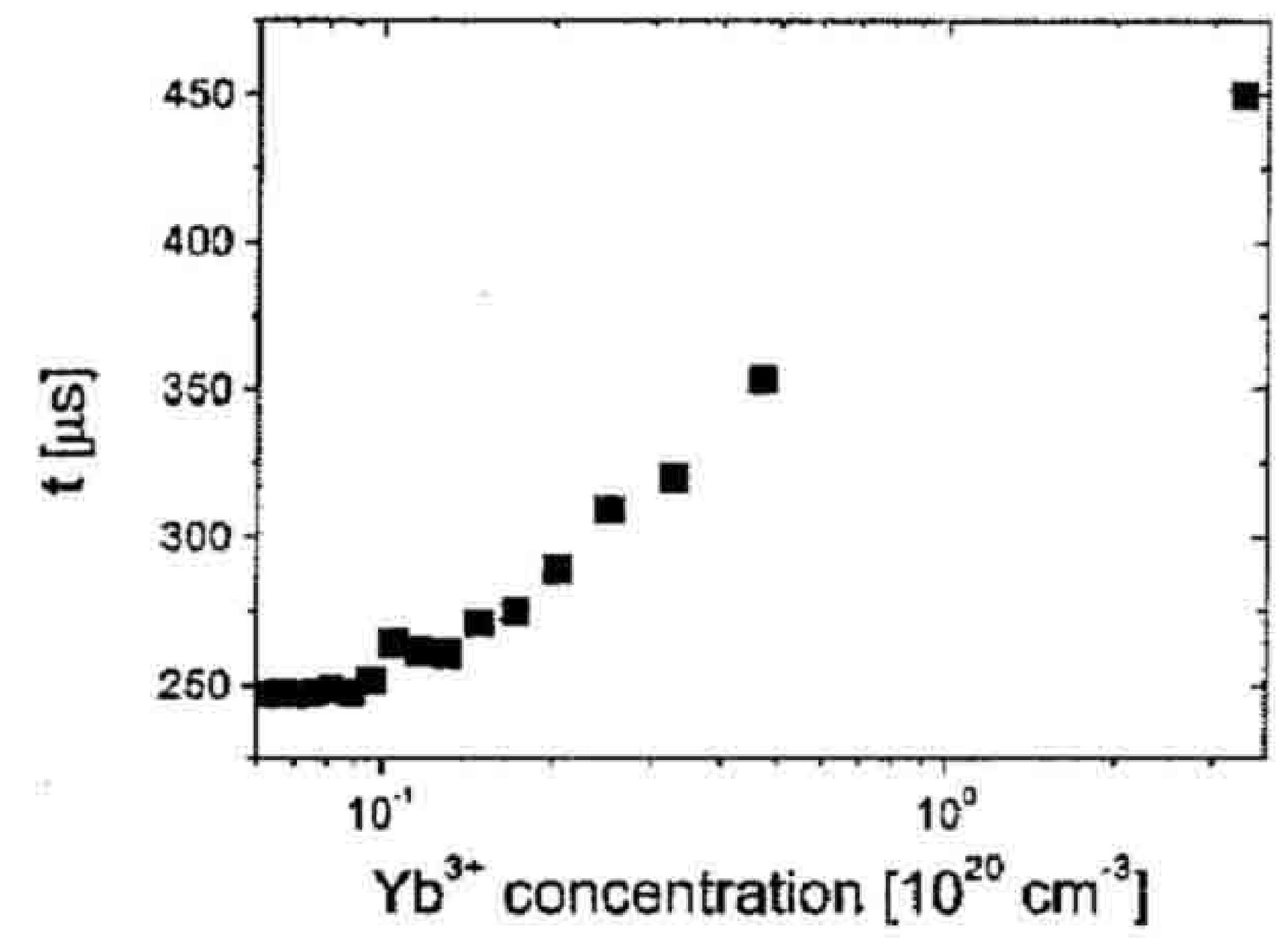

Fig. 2. Lifetime of the Yb(1.62 at.%):YVO$_4$ crystalline powder immersed in glycerin. The plotted Yb-concentration is an average concentration in suspension.

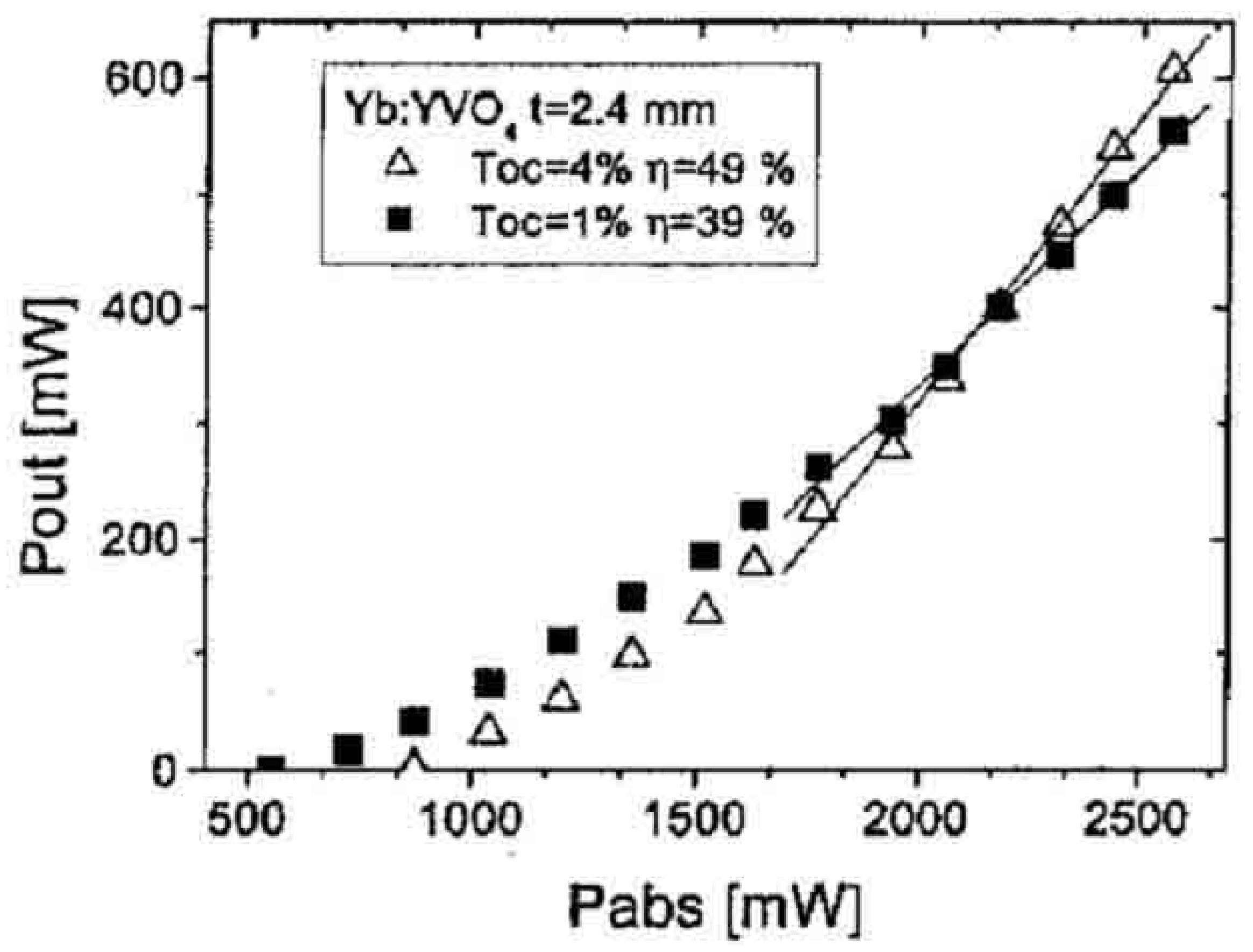

Fig. 3. Output power versus absorbed pump power of a cw Yb:YVO$_4$ laser.

Yb^{3+} laser materials the obtained laser efficiency of $Yb:YVO_4$ is lower; however, it could be increased by increasing the pump power, as one can see from the nonlinear input–output dependence.

In conclusion, we have demonstrated, for the first time to our knowledge, an efficient $Yb:YVO_4$ laser with diode laser pumping. Taking into account the strong and comparatively broad absorption band near 985 nm, the extremely low quantum defect of 3.5%, and the broad emission band of $Yb:YVO_4$, this material looks promising for high-power thin-disk lasers as well as for femtosecond pulse generation.

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